Quantitative Chemical Mass Transfer in Coastal Sediments During Early Diagenesis: Effects of Biological Transport, Mineralogy, and Fabric--Phase III

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Thrust: FNC Organic Mine Countermeasures

LONG-TERM GOAL

The long-term goal of this study is to develop a better mechanistic and quantitative understanding of the effects of biologically-enhanced transport, mineralogy, sediment fabric, and particle surface chemistry on biogeochemical reactions occurring in coastal sediments. Specifically, we plan to integrate quantitative expressions of the strongly coupled effects of bioirrigation, bioturbation, mineralogy, and sediment fabric on chemical mass transfer from field and laboratory mesocosm studies using numerical modeling.

OBJECTIVES

The short term objective during FY00 was to (1) achieve a better understanding of the bio-geologic dynamics of estuarine sediments by quantitatively describing the relationship between bioturbation, sediment physical properties, microfabric and permeability, (2) perform a statistical analysis of burow networks on the cm scale and pore network on the μm scale using sediments recovered from the joint field sites and laboratory mesocosm experiments, (3) to accurately compute the permeability coefficient from two-dimensional images using EMT, and verify results with in situ, mesocosm and laboratory permeability measurements, and (4) to quantify the development of permeability as a function of colony development (using the entire mesocosm as the permeameter).

APPROACH

The approach is an integration of field sampling, controlled experiments in laboratory mesocosms, image analysis and numerical modeling. Laboratory mesocosms provide an environment where time-series studies of sediment characteristics including sediment behavior (e.g., aggregation, disaggregation, resuspension, remolding and compaction), properties (e.g., porosity, density and permeability) and microfabric can be studied under controlled conditions. The tank sediments are derived from estuarine bottom sediments at our field site and populated with only one species of bottom fauna at a time in order to limit variables and aid in our interpretation of field data. The characterization of sediments in the mesocosms is focused primarily on microfabric, because sediment microfabric analyses, combined with image analysis, is the most effective method for identifying changes within the sediment medium. Experimental results are measured by laboratory analyses of bulk physical properties. Macro/microscopic analyses of sediment fabric utilizing x-radiography, CT scanning and transmission electron microscopy are quantified using standard image analysis techniques; significant effort is being expended in refining the techniques for defining particle edges, organic matter and pore space in the fine-grained sediments recovered from our experimental site. Biologically influenced fluid flow is being modeled and measured experimentally. This work is closely coordinated with Y. Furukawa (Naval Research Laboratory) who is analyzing pore fluids, bulk geochemistry and vertical distribution of ^{13}C; Karla Koretsky (Western Michigan University) and Philippe Van Cappellen (Utrecht University, The Netherlands) who are incorporating our results into the RT model, STEADYSED; and Sam Bentley (Louisiana State University) who is evaluating spatial and temporal particle mixing.

FY00 tasks included:

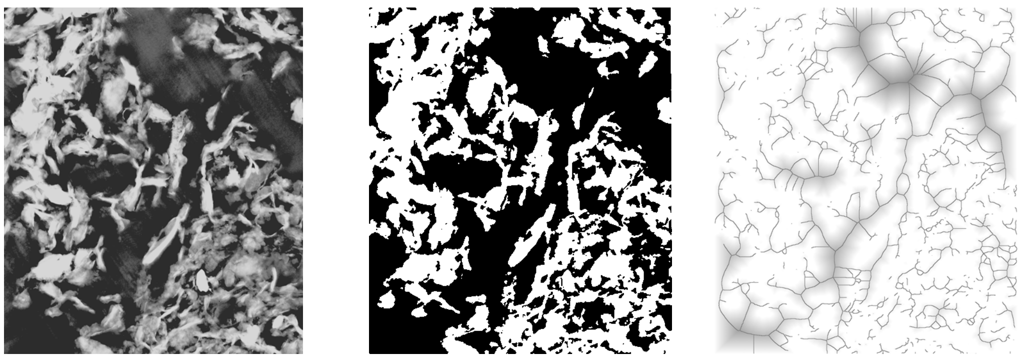
- Microfabric characterization (quantification) of burrow walls, ejecta mounds and matrix sediment. A statistical study is underway to assess biologically induced fabric variability noted in samples.
- Analysis of 3-D data sets from CT scans to model fluid flow within 2-D areas (vertical and horizontal) within a volume of "effective medium"; to be validated using one tank where the entire mesocosm functions as the head of a constant head permeameter and the evolution of permeability is measured as a function of burrow development with time.
- Extending the 2-D models based on effective medium theory (Vaughan et al., 2000; Vaughan and Lavoie, 2000) to 3-D (leveraged using internal NRL core funding).

WORK COMPLETED

- Microfabric characterization, comparison and modeling (of burrow walls, ejecta mounds and matrix sediment) completed for experiments involving Schizocardium sp.
- Burrow modeling and model (EMT) sensitivity study completed. Results submitted to Journal of Hydraulic Engineering.
- Analysis of permeability evolution as a function of colonization is ongoing; see initial results below.
- Extension of 2D to 3D modeling is part of an ongoing student dissertation.

RESULTS

Burrows, ubiquitous in shallow-water sediments, create porosity and permeability variability over spatial scales ranging from µm to cm. A high-resolution estimate of porosity and permeability of the matrix sediment surrounding the burrows is derived from microfabric analysis of the pore network (Figure 1). In addition, an estimate of fluid flow though burrows is obtained by modeling the burrows as pore space using Effective Medium Theory (Figure 2). Initial in situ and modeling results indicate that in heavily bioturbated sediments, the permeability of the matrix sediment contributes little to the permeability since most fluid flows through burrows. The burrowing activities of *Schizocardium* sp. induce significant sediment microfabric reordering that results in differential permeability on the microscale. Because most burrows are too fragile to survive handling, and the volume of sediment usually contains to few burrows to generalize their effect, we constructed a permeameter using an aquarium that functions as a falling head in order to measure actual burrow influence on permeability (Figure 3). The aquarium was layered with mud collected from the NRL Mississippi Sound experimental site and allowed to settle for 3.5 months. The aquarium was populated with *Schizocardium* sp (acorn worms) at a population density of $287/m^2$ on June 10, 2000. The population density was increased to $430/m^2$, a density similar to that in the natural environment, on August 25, 2000. Whole tank permeability is measured periodically to monitor changes in permeability during maturation of the worm colony. Permeability decreased during the settling stage to 9.0×10^{-7} cm/s, but increased slowly to 2.15×10^{-6} 72 days after the initial worm introduction. Permeability is expected to increase with the second addition of worms. This experiment is in progress.



1. **2.** **3.**

Figure 1. Pore space characterized using UTHSCSA Image Tool. Steps include 1. Negative image, 2. Binary image (image porosity), 3. Skeletonization (network distribution) and Euclidean Distance Mapping (width, length). A method for quantifying microfabric of fine-grained sediments includes estimation of clay mineralogy, clay characteristics (e.g., CEC), orientation and distribution of clusters (Lavoie and Anandarajah; Anandarajah and Lavoie).

Digitized x-radiograph — Void space within burrows — Skeletonization and EDM

Figure 2. From a digitized x-radiograph, burrows can be quantified using established techniques and the resulting descriptors used as input parameters. Permeability through burrows can then be estimated using EMT modeling.

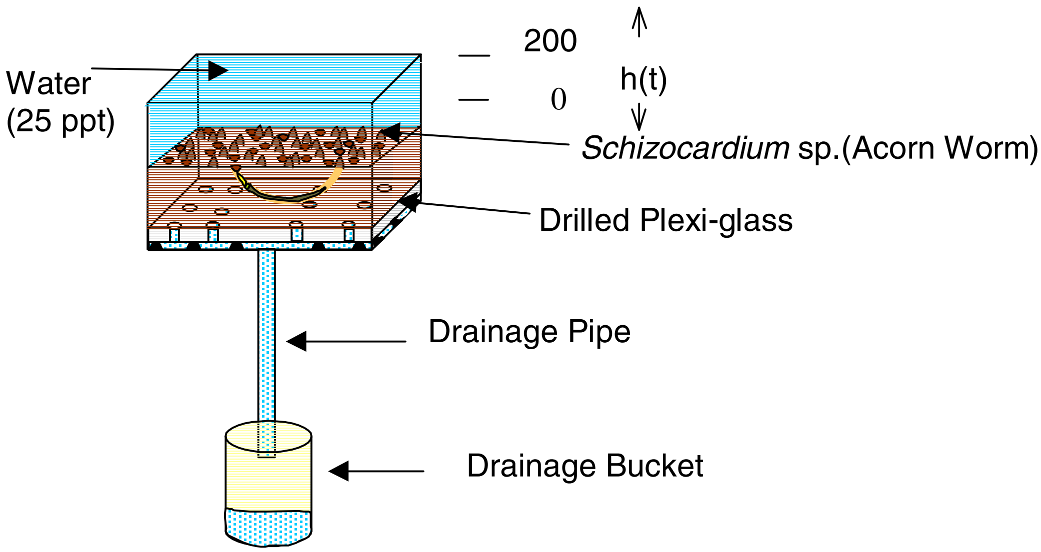


Figure 3. Schematic of the whole mesocosm permeameter which allows the measurement of permeability evolution as burrowing colonies mature.

IMPACT/APPLICATION

A better understanding and mathematical description of biologically-enhanced transport, sediment fabric and particle surface chemistry during shallow diagenesis will allow us to better model and predict the fate and transport of particles and associated pollutants, By concentrating on fine-grained sediments over the next few years, we hope to make a significant contribution to harbor pollution solutions. In addition, by understanding the effect of fabric changes during diagenesis, we will be able to better predict sediment physical and geoacoustic properties of interest to the MCM community, (predicting mine burial in shallow coastal regions) and the acoustic community for modeling acoustic propagation.

TRANSITIONS

Techniques for quantitative characterization (2D and 3D) of sediment macro and microfabric will be transitioned to other ONR-funded programs including the High-frequency Sound Interaction in Ocean Sediments: Modeling Environmental Controls DRI. It is anticipated that results from this effort will contribute to applied environmental programs in the future.

RELATED PROJECTS

This project has leveraged the NRL 6.1 core program (Microenvironmental Studies) for support, particularly for the field effort, and will continue to do so. Microfabric results have been used in modeling efforts to predict permeability and will undoubtedly continue to benefit other programs with similar requirements. For example, the ONR High Frequency Sound Interaction DRI requires quantitative pore space and particle geometry data for prediction of permeability and porosity and related Biot parameters used in acoustic propagation modeling.
This project is one portion of a collaborative effort titled “Quantitative Chemical Mass Transfer in Coastal Sediments During Early Diagenesis: Effects of Biological Transport, Mineralogy and Fabric “

with Drs. Yoko Furukawa of NRL (sediment geochemistry and numerical modeling), Sam Bentley of LSU, (particle mixing and sedimentary fabric), Carla Koretsky and Phillippe Van Cappellen (sediment geochemistry and continuing development of STEADYSED).

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